Update On SLD Engineering Tools Development

Dean Miller

Mark Potapczuk

Thomas Bond

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Outline

- Background
- SLD Technology Roadmap
- Evolution of SLD Engineering Tool Project Plan
- Summary Of SLD Engineering Tool Research
- Concluding Remarks

Why Develop SLD Engineering Tools?

- A draft regulation affecting aircraft operations in SLD icing conditions is expected to be released in 2006
- Aircraft manufacturers must be able to design for SLD icing conditions and provide "proof of performance" to certification authorities
- SLD engineering tools will be needed to provide a means of compliance (along with the possibility that natural icing flight testing may be required)
  - **icing tunnels**
  - **icing tankers**
  - **analytical codes**

SLD Tool Development – International In Scope

- An Ad Hoc group of international icing researchers formed a partnership to develop SLD engineering tools
- Composed of national and private research organizations and academic institutions
- Group has expanded to include other organizations with expertise and resources

CePR (France) INTA (Spain) NASA (US) ONERA (France) QinetiQ (UK)	Research Organizations
CAA (UK) FAA (US)	Airworthiness Authorities
Cranfield University (UK) Univ. College Of London (UK) University Of Illinois (US) Wichita State University (US)	Universities
BAE Systems (UK) Airbus (UK)	Other Attendees

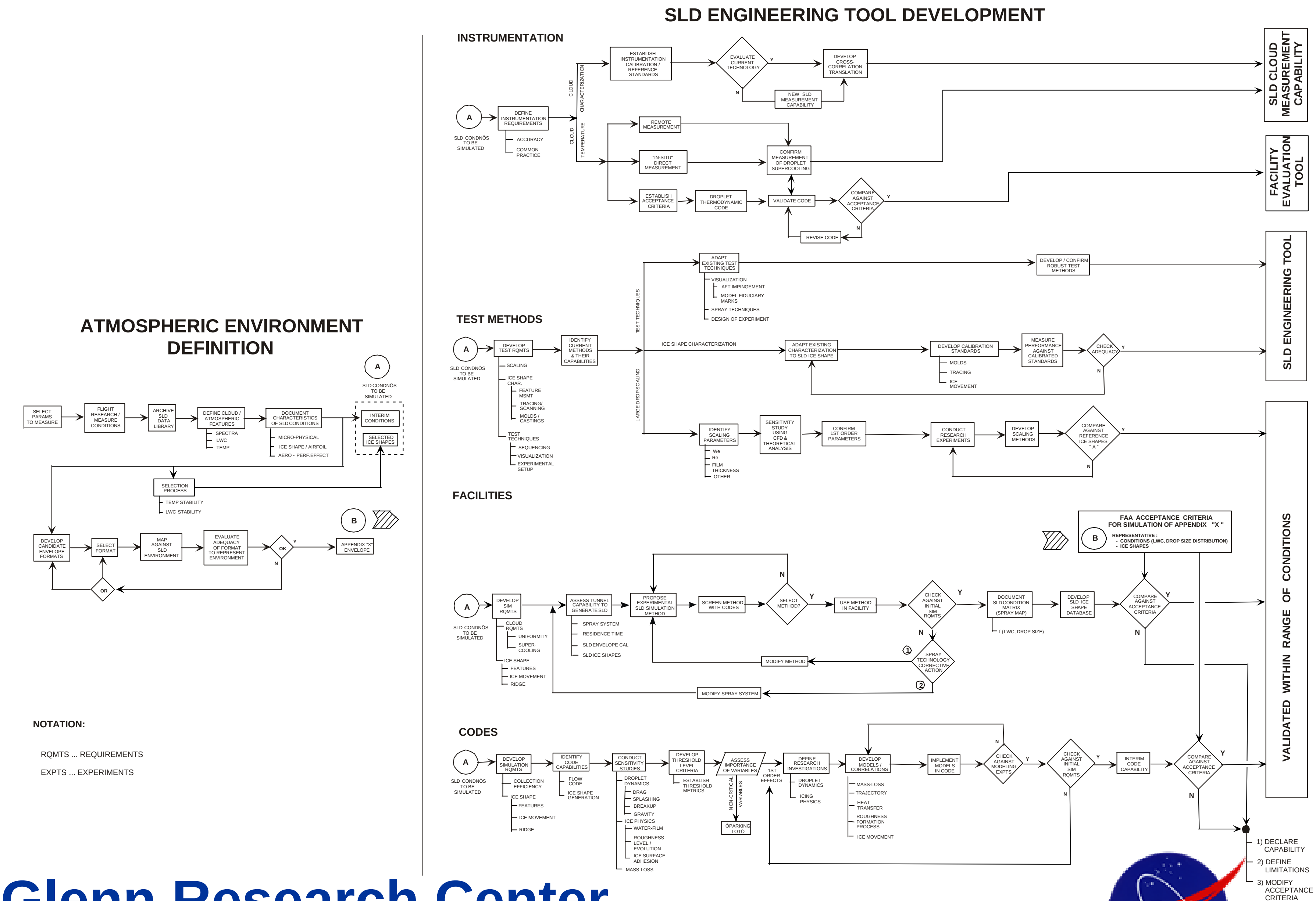
SLD Technology Roadmap

- Development of SLD engineering tools was recognized to be a very complex effort
  - **Fundamental and applied research required**
  - **Many inter-related tasks (w/ time dependencies)**
  - **Different, but inter-connected technical elements**

- NASA and it's international partners developed an SLD Technology Roadmap
  - **To provide a comprehensive plan**
  - **Identify overall process for resolving issues**
  - **Identify inter-relationships between technical tasks**
  - **Provide a documented guideline for developing SLD tools**

Version 2.3
3/29/02

SLD TECHNOLOGY ROADMAP



SLD Tool Project Plan Evolution

- It was desired to take the ideas embodied in the roadmap and turn them into a project plan that included the following elements
  - **Adjustments for priorities**
  - **Task identification**
  - **Resource identification**

- A draft SLD Engineering Tool Project Plan & WBS was developed and presented for comments to the FAA & international partners
  - **The draft SLD Tool Project Plan contained a Gantt chart**
  - **The WBS associated with this Project Plan was a text document with a numerical index of tasks corresponding to tasks in the Project Plan**

SLD Tool Project Plan Evolution

- **The feedback from this review was as follows:**
  - **The SLD Roadmap was comprehensive**
  - **To implement the entire Roadmap might extend beyond 2006**
  - **Some research tasks could be viewed as longer term objectives and of lower priority**
  - **Viewed from a certification perspective, some tasks were deemed higher priority than others**

- **Ability to simulate SLD in facilities (tunnels, tankers)**
- **Ability to scale SLD conditions**

SLD Tool Project Plan Evolution

This review process led to modification of the draft project plan into the following 4 primary technical areas:

- **SLD Simulation Capability** … simulate SLD conditions and generate SLD ice shapes with facilities and codes
- **Scaling Capability** … scale SLD icing conditions based on facility or test article constraints
- **Instrumentation Capability** … accurately measure SLD icing conditions
- **Universal Methodology** … translate SLD simulation methodologies developed using NASA IRT into a "generic" form which could potentially be adapted by other icing research facilities

SLD Tool Project Plan Evolution

- In this form the project plan has undergone further review by
  - FAA/JAA/TC Technical Team
  - Ice Protection Harmonization Working Group
  - Aircraft Manufacturers in Wichita Kansas
- The SLD Engineering Tools Project Plan has been updated to the current version 1.0 based on comments received from these reviews
- A summary of the version 1.0 WBS will now be presented along with an update on the status of a few selected SLD research tasks

WBS Level 1 Elements

1.0 Simulation	• Reproduction of SLD conditions in facilities • Generation of SLD ice shapes in facilities • Prediction of ice shapes with codes
2.0 Scaling	• Scaling methods for SLD icing conditions - testing subscale models - scale desired test conditions within facility capabilities
3.0 Instrumentation	• Measurement capability to quantify attributes of SLD icing conditions - cloud conditions - ice shape features
4.0 Universal Methodology	• Capture technology / methods and document in form which can be customized for adaptation to other icing facilities and organizations

Layout Of WBS 1.0 Simulation

- **1.1** Dev SLD Rqmts
- **1.2** SLD simulation With Tunnel
  - **1.2.1** Reproducing SLD Condns
  - **1.2.2** Simulating SLD Ice Shapes
  - **1.2.3** Confirm Tunnel Simulation
- **1.3** SLD simulation With Codes
  - **1.3.1** Ice Shape Prediction
  - **1.3.2** Impingement Limit
  - **1.3.3** Collection Efficiency
  - **1.3.4** Thermal Analysis
  - **1.3.5** Develop Models
- **1.4** SLD Simulation With Tankers
  - **1.4.1** Reproducing SLD Condns
  - **1.4.2** Simulating SLD Ice Shapes
  - **1.4.3** Confirm Tanker Simulation

1.1 Simulation Requirements

- Requirements (or metrics) need to be defined to provide a “target" for SLD simulation in quantified terms
- These requirements provide guidance about:
  1) essential features or characteristics to be simulated
  2) how accurately these characteristics need to be simulated
- Developed by means of sensitivity studies
- Derived taking into account recommendations from the IPHWG

WBS	Description	Status*	Org
1.1	**Develop simulation requirements**	**I**	**NASA, ONERA QinetiQ**

*** Status: TBD = to be determined, C=completed, I = in progress, F = future effort**

1.2 SLD Simulation With Icing Tunnel

WBS	DESCRIPTION	STATUS*	ORG
1.2.1	Reproducing SLD Cloud Conditions		
1.2.1.1	Assess current capability to produce SLD	I	NASA
1.2.1.2	Develop methods to generate SLD cloud		
1.2.1.2.1	Investigate & document constant or time varying Icing condition in SLD encounters	I	NASA
1.2.1.2.2	Develop cloud sequencing method	F	NASA
1.2.1.3	Determine residence time of supercooling		
1.2.1.3.1	Evaluate droplet supercooling with thermodynamic codes	I	QinetiQ, ONERA,
1.2.1.3.2	Validate droplet thermodynamic code	F	NASA
1.2.1.4	Document range of LWC and MVD vs Appendix SLD	F	NASA
1.2.1.5	Document drop size distribution vs App SLD	F	NASA

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Current Activities - Facility Capability
NASA Icing Research Tunnel SLD Calibration

Location: Glenn Research Center

Principle Investigator: Robert Ide

- Drop size calibration is complete MVD: 50 to 225 μm
- Need to improve LWC measurement confidence
  - Currently have used the icing blade for SLD LWC calibration
  - Have defined LWC/MVD for airspeeds of 100 to 200 knots
- No testing yet on large droplet spray bar conditions & resultant ice shape versus SLD bi-modal spectra. Test planned for later this summer.

1.2 SLD Simulation With Icing Tunnel

WBS	DESCRIPTION	STATUS*	ORG
1.2.2	Simulating SLD Ice Shapes		
1.2.2.1	Compare icing wind tunnel shapes to natural shapes		
1.2.2.1.1	Compile database of natural ice shapes		
1.2.2.1.1.1	Assess existing database	C	NASA
1.2.2.1.1.2	Acquire new flight ice shape data	I	NASA
1.2.2.1.2	Compile tunnel ice shapes	F	NASA
1.2.2.1.3	Compare natural & tunnel ice shapes	F	NASA
1.2.2.2	Evaluate repeatability of facility for ice shape generation	F	NASA
1.2.3	Confirm adequacy of simulation	I	NASA

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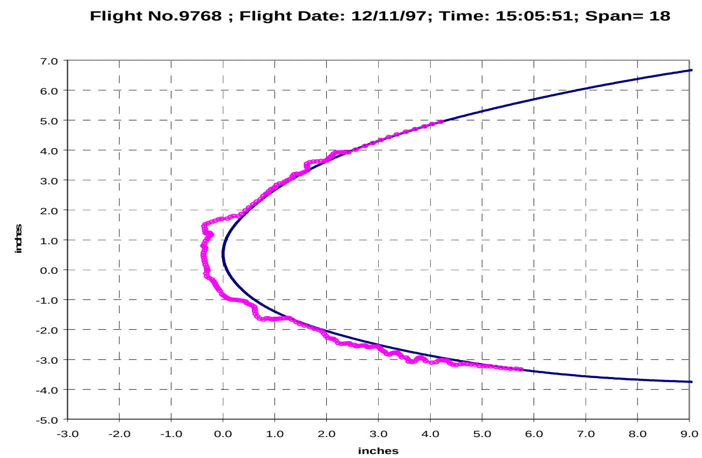
Current Activities – Acquire Flight Ice Shapes

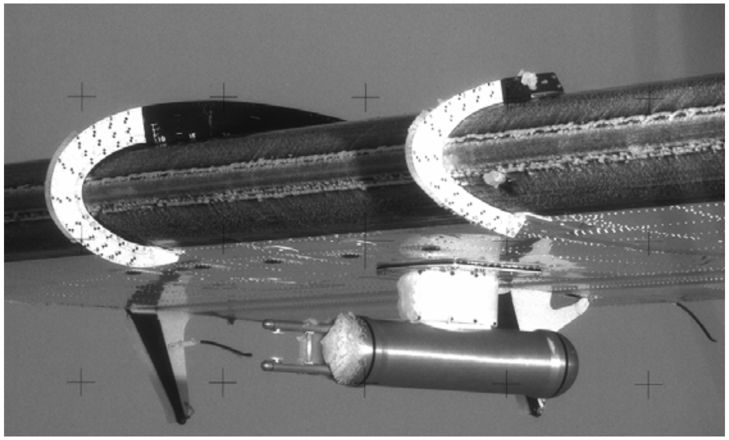
Location: **Glenn Research Center**

Principle Investigator: **Tom Ratvasky**

Objectives:

- **Acquire additional SLD flight ice shapes, add to database**
- **Fly Twin Otter into SLD conditions**
- **Allow ice to build on wing, and photograph resulting ice accretion with stereo camera system**





Status:

- **Analyze data from winter 2002-2003, acquire more during upcoming winter of 2003-2004**

1.3 SLD Simulation With Codes

WBS	DESCRIPTION	STATUS*	ORG
1.3.1	**Ice Shape Prediction**		
1.3.1.1	**Droplet Dynamics**		
1.3.1.1.1	Analysis of droplet dynamics	I	Iowa State, WSU
1.3.1.1.2	Droplet dynamics experiments	TBD	
1.3.1.1.3	Develop droplet dynamics model	TBD	
1.3.1.2	**Droplet Splashing**		
1.3.1.2.1	NASA droplet splashing experiment	F	NASA, WSU
1.3.1.2.2	Cranfield droplet splashing experiment	F	Cranfield Univ.
1.3.1.2.3	Analytical modeling of splash/impact dynamics	F	Univ. College of London, QinetiQ
1.3.1.2.4	ONERA droplet splashing experiment	F	ONERA
1.3.1.2.5	Develop droplet splashing model	F	NASA, ONERA, QinetiQ

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Current Activities – Droplet Dynamics

Location: Wichita State University

Principle Investigator: Jason Tan & Michael Papadakis

Objective:

- Identify droplet dynamic issues relevant to SLD icing
  - Droplet deformation & breakup prior to impact
  - Droplet splash/deposition/bounce
  - Near-wall effects
  - Supercooling large droplets
  - LWC measurement of large MVD spray cloud
- AIAA paper # 2003-392

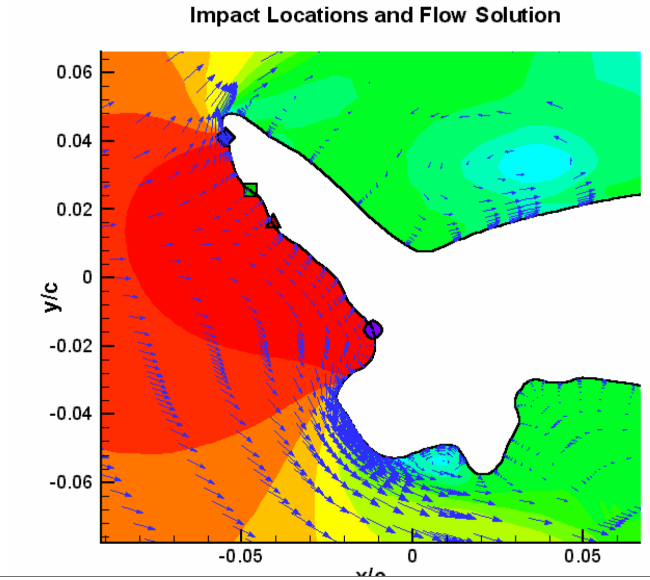
Current Activities - Droplet Splashing/Mass Loss
Numerical Splashing Analysis

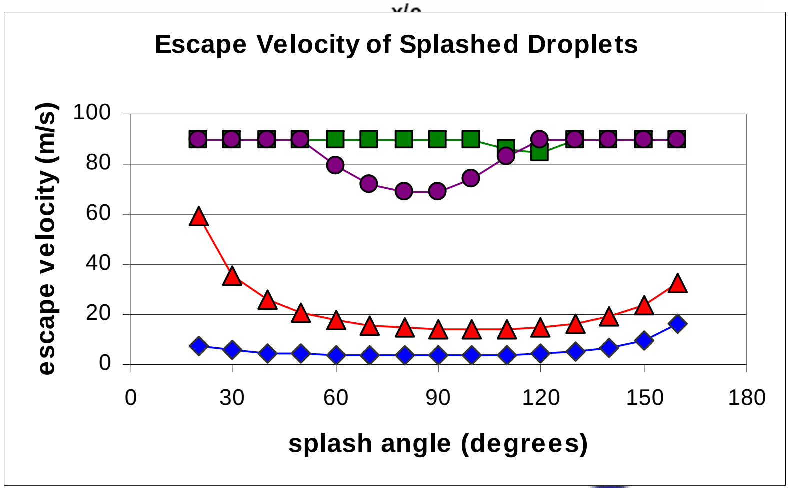
Location: NASA Glenn and CWRU

Principle Investigator: Adam Rutkowski

Objectives:

- Use CFD tools to calculate trajectories of splashed droplets from initial impact locations
- Determine if splashed droplets re-impinge or are swept downstream of the airfoil
- Perform parametric studies to determine size, velocity, and splash angle of droplets that will re-impinge on clean or iced airfoil



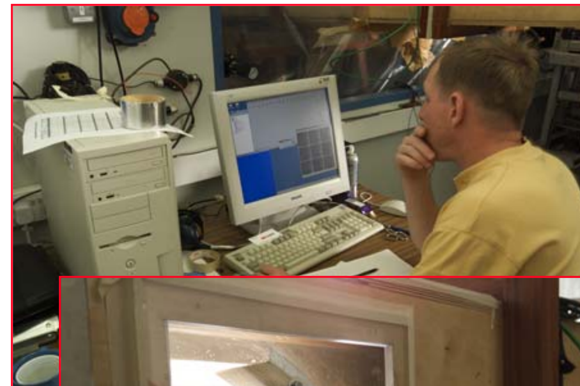


Current Activities - Droplet Splashing/Mass Loss
NASA/FAA/QinetiQ Splashing Visualization Test

Location: Aerospace Composite Technologies - Luton Icing Tunnel

Principle Investigator: Dean Miller

Objectives:



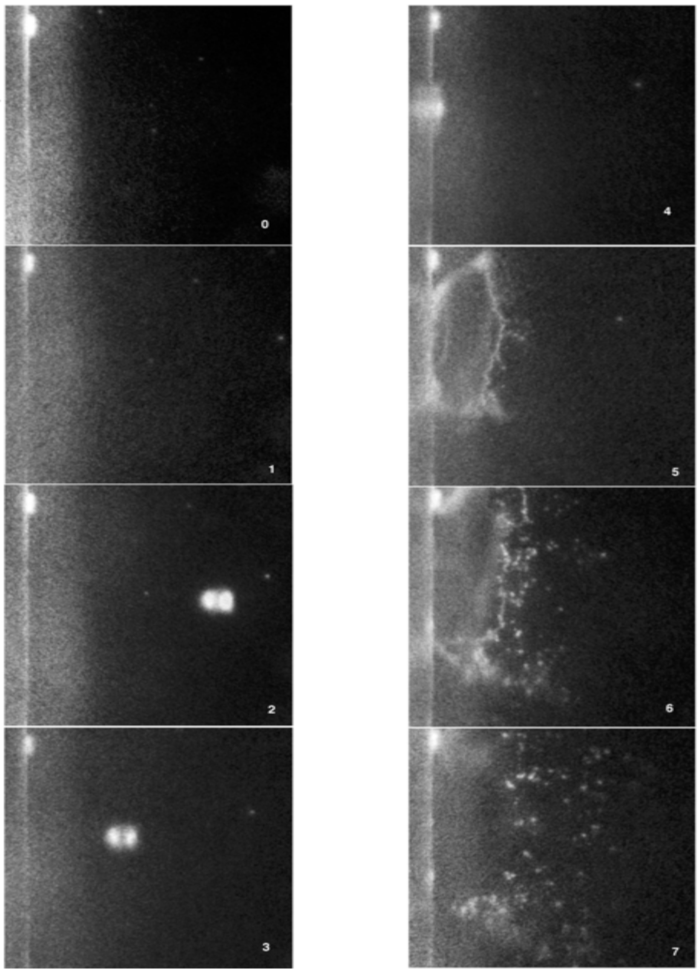
- Demonstrate ability to capture high speed image sequences in spray
- Quantified incoming droplet velocity, size, splash height (D>100um)
- Splashed ejecta too small to measure
- Identified limitations of camera system when used to image in spray cloud
  - Background noise level due to scattered light, limited resolution
  - Camera system may be more suited for use with single-droplet splash experiments vs spray cloud

Current Activities - Droplet Splashing/Mass Loss

Visualization Experiments for Droplet Splashing

Images Taken At NASA Glenn Research Center DrIFT

ASpray 04



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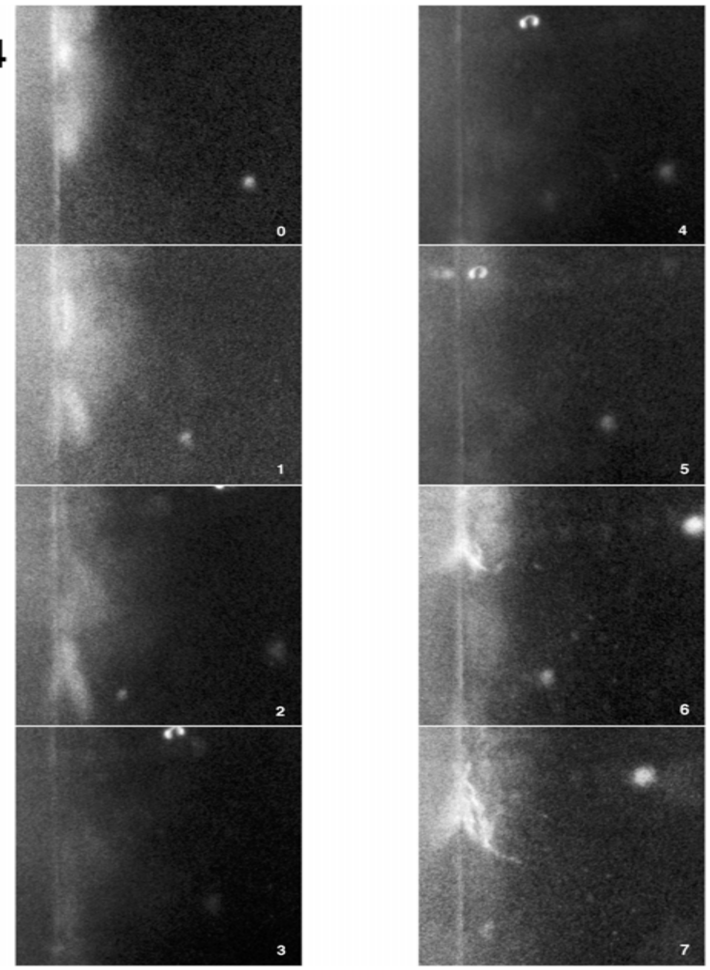

1.3 SLD Simulation With Codes

WBS	DESCRIPTION	STATUS*	ORG
1.3.1	Ice Shape Prediction (contd)		
1.3.1.3	Mass Loss		
1.3.1.3.1	Ice mass measurements on airfoils	I	NASA, QinetiQ
1.3.1.3.2	Water runback mass measurements	I	QinetiQ
1.3.1.4	Ice Sliding		
1.3.1.4.1	Review previous test efforts	I	NASA, QinetiQ
1.3.1.4.2	Assess need for further work	F	NASA, QinetiQ
1.3.2	Icing Impingement Limit	TBD	
1.3.3	Collection Efficiency		
1.3.3.1	Effect of splashing on collection eff.	I	WSU, FAA, NASA
1.3.3.2	Clean geometry collection eff. study	I	WSU, FAA, NASA
1.3.3.3	SLD ice shape collection eff.	I	WSU, FAA, NASA

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Current Activities - Droplet Splashing/Mass Loss

Location: Glenn Icing Research Tunnel (US)

Principle Investigator: Mark Potapczuk

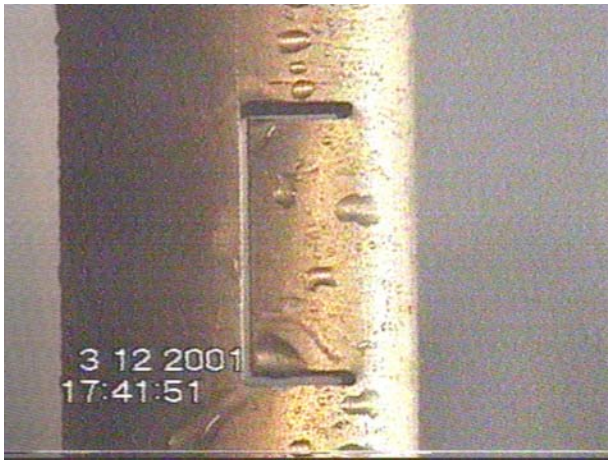
Objectives:

- Determine whether large droplet encounters result in mass loss
- Directly measure the mass of ice deposited on a well-defined target geometry under Appendix C and SLD conditions
  - Method 1: maintain K_0, A_c, and velocity over range of drop sizes
  - Method2: maintain A_c, β_o, and freezing fraction over range of model sizes and drop diameters
- Determine ice shapes with LEWICE assuming no splashing
- Compare ice shape tracings to LEWICE results and compare measured and calculated ice mass values
- AIAA paper #2003-0387

Current Activities - Droplet Splashing/Mass Loss
QinetiQ/NASA Mass Loss Test

Location: Aerospace Composite Technologies - Luton Icing Tunnel

Principle Investigator: Roger Gent



Objective:

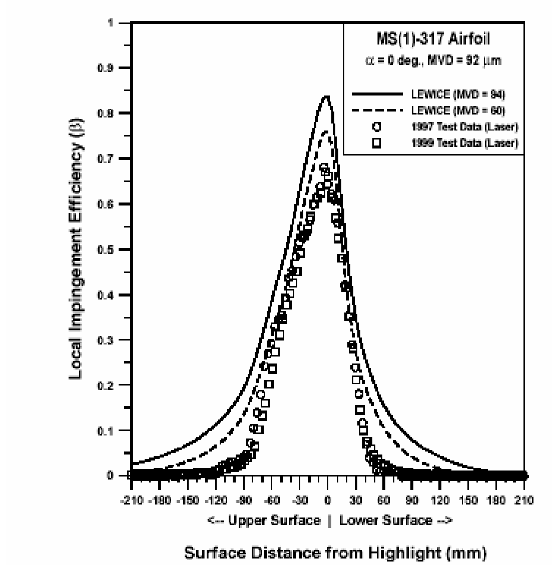
- Measure mass loss due to splashing
- Develop empirical correlation for mass loss as function (V, d, film thickness)
- Investigate mass loss using 3 methods
  - Aspirated ellipse
  - Comparison of NevZorov TWC and NevZorov LWC
  - Mass loss estimate based on measured mass of accreted ice
    - Correlated mass loss tend with splashing "K" factor
    - Agreed with NASA mass loss trends
- AIAA-2003-0389 Paper

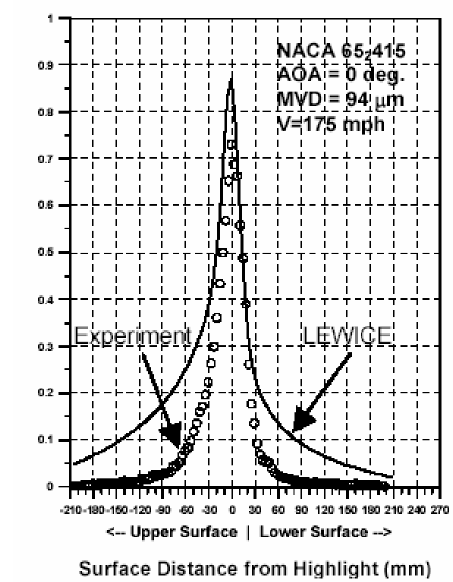
Current Activities – Collection Efficiency
FAA/NASA/WSU Collection Efficiency Tests

Location: NASA Glenn Icing Research Tunnel (US)

Principle Investigator: Michael Papadakis

Objective: Measure collection efficiency in SLD





SLD impingement on an MS-317 airfoil (LEWICE vs. experiment)

SLD impingement on a NACA 65$_2$415 airfoil (LEWICE vs. experiment)

1.3 SLD Simulation With Codes

WBS	DESCRIPTION	STATUS*	ORG
1.3.4	**Thermal Analysis**		
1.3.4.1	SLD Runback Ice	F	NASA, Cessna
1.3.5	**SLD Model Development**		
1.3.5.1	Development of proposed SLD model	F	NASA, ONERA, QinetiQ
1.3.5.2	Implementation	F	NASA, ONERA, QinetiQ
1.3.5.3	Validation Testing	F	NASA, ONERA, QinetiQ
1.3.5.4	Documentation	F	NASA, ONERA, QinetiQ

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1.4 Simulation With Tankers

1.4 SLD Simulation With Tankers — **1.4.1** Reproducing SLD Condns — **1.4.2** Simulating SLD Ice Shapes — **1.4.3** Confirm Tanker Simulation

Except for any modifications to allow for the unique capabilities of tanker systems, these tasks should be similar in nature to those required to simulate SLD in icing wind tunnels. It is expected that the organizations proposing to simulate the SLD environment with icing tankers, would provide more detail for work in this area.

WBS	Description	Status*	Org
1.4.1	Reproducing SLD conditions	TBD	Raytheon, Cessna
1.4.2	Simulating SLD shapes	TBD	Raytheon, Cessna
1.4.3	Confirm adequacy of tanker simulation	TBD	Raytheon, Cessna

* Status: TBD = to be determined, C=completed, I = in progress, F = future effort

2.0 Scaling

Scaling is required when:

- Facility cloud conditions need to be adjusted with respect to model scale
- Desired icing cloud test conditions lie outside icing facility capabilities

WBS	DESCRIPTION	STATUS*	ORG
2.1	Assess Current Scaling Methods		
2.1.1	Develop scaling requirements	TBD	
2.1.2	Perform SLD scaling experiments	I	NASA
2.1.3	Water film scaling studies	I	INTA, NASA
2.1.4	Summary report	F	NASA
2.2	Incorporate New Findings	F	NASA

*** Status: TBD = to be determined, C=completed, I = in progress, F = future effort**

Current Activities - Scaling Methods

Location: Glenn Icing Research Tunnel (US)

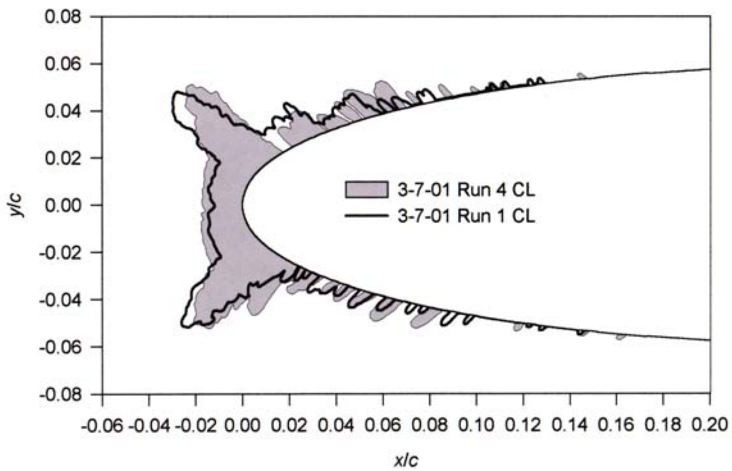
Principle Investigators: Dave Anderson & Paul Tsao

Average-Velocity Scaling from 120µm

NACA 0012 with A_c = constant

Case 235SLD

	c, in	t_{tot}, °F	V, mph	MVD, µm	LWC, g/m³	τ, min	β_0, %	n
Reference	36	22	173	120	.69	15.8	94	0.3
Scale	36	25	220	50	.58	14.7	86	0.3



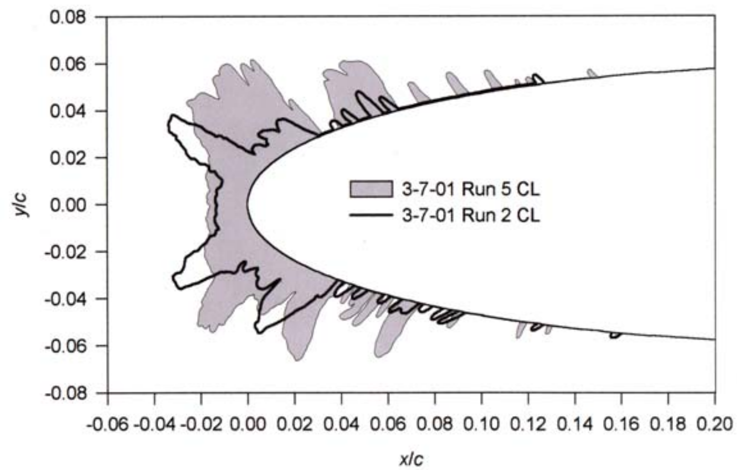
"Good" agreement:
successfully scaled to 50µm from MVD up to 120µm

Average-Velocity Scaling from 175µm

NACA 0012 with A_c = constant

Case 225SLD

	c, in	t_{tot}, °F	V, mph	MVD, µm	LWC, g/m³	τ, min	β_0, %	n
Reference	36	19	173	175	.99	11.0	96	0.3
Scale	36	23	248	50	.75	10.1	87	0.3



Poor agreement:
scaling from 175µm to 50µm not successful

Current Activities - Scaling Methods

<u>**Location:**</u> **INTA flow lab/wind tunnel (Spain)**
<u>**Principle Investigator:**</u> **Alejandro Feo**
<u>**Objective:**</u> **Water film thickness scaling effects**

- **Develop two spray systems: the first will simulate Appendix C drop sizes and *LWC*'s; the second to simulate SLD conditions**
- **Measure the water film thickness for these conditions and correlate the film thickness with non-dimensional parameters such as the Weber and Reynolds numbers**
- **Tests will eventually incorporate film-thickness probe in a rounded shape to represent airfoil configuration**

3.0 Instrumentation

3.0 Instrumen-tation — 3.1 Rqmts — 3.2 LWC — 3.3 Droplet Size — 3.4 Cloud Temp — 3.5 Ice Shape — 3.6 Humidity

- **The tasks undertaken in the sections 1.0 & 2.0 as well as the general process of testing under SLD conditions requires the use of accurate measurement devices for quantities such as water droplet size, liquid water content, temperature, and humidity.**

- **Instruments to perform these measurements are currently available for Appendix C icing conditions.**

- **It is the intent of this element of the project plan to identify the requirements for such instruments with respect to SLD conditions and to assess the abilities of current instruments to satisfy those requirements.**

3.0 Instrumentation

WBS	DESCRIPTION	STATUS*	ORG
3.1	Requirements		
3.1.1	Sensitivity studies of ice shapes to msmts	F	NASA
3.1.2	Survey users on instrumentation rqmts	F	
3.1.2.1	Identify user requirements	F	NASA, FAA
3.1.2.2	Evaluate user requirements	F	NASA, FAA
3.1.2.3	Document user requirements	F	NASA, FAA
3.1.3	Define operational rqmts of instruments	F	NASA
3.2	Liquid Water Content Measurement		
3.2.1	Instrumentation assessment	I	NASA
3.2.2	Reference measurement devices		
3.2.2.2	LWC measurement iso-kinetic (method1)	I	WSU, FAA
3.2.2.3	LWC measurement iso-kinetic (method2)	TBD	Cranfield
3.2.3	Correlate other instruments to reference	F	NASA

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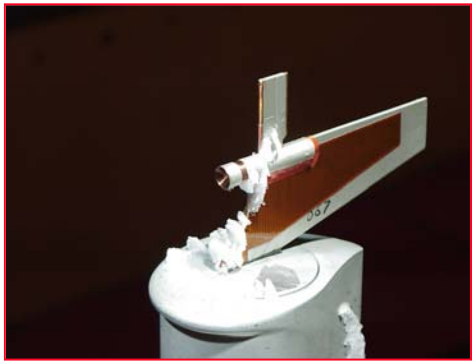
Current Activities – LWC Instrumentation
Instrumentation Assessment

Location: **Glenn Icing Research Tunnel**

Principle Investigators: **Dean Miller & Ed Emery**

Objectives:



- Characterize liquid water content probe response and accuracy in SLD
- Subject hot-wire probes to SLD icing conditions
  - **Nevzorov LWC/TWC**
  - **King LWC**
  - **New sensors under development**
- Attempt to quantify elements of measurement uncertainty
  - **Due to variation of tunnel parameters**
  - **Collection efficiency uncertainty (method & MVD)**
  - **Sensor gain**

Current Activities – LWC Instrumentation

Location: Wichita State University

Principle Investigators: Jason Tan & Michael Papadakis

Objectives:

- Develop a reference LWC probe
  - Provide a more accurate measurement of LWC
  - Serve as a “primary” LWC standard
  - Reference / calibrate other LWC probes to this device
  - Provide quantified / traceable accuracy
- Resolve current ambiguities in LWC measurement
  - Differences when same probe tested in different tunnels
  - Response variations in LWC probes due to drop size
  - Uncertainties introduced by collection efficiency
- FAA grant (Sept 2002 – Jan 2004)

3.0 Instrumentation

WBS	DESCRIPTION	STATUS*	ORG
3.3	**Drop Size Measurement**		
3.3.1	Instrumentation assessment	F	NASA, MSC
3.3.2	Evaluate performance of instruments	TBD	
3.3.3	Identify candidate instruments for use	TBD	
3.4	**Cloud Temperature Measurement**		
3.4.1	Instrumentation assessment	F	NASA
3.4.2	Develop new measurement method	TBD	
3.5	**Ice Shape Measurement**		
3.5.1	Examine rqmts for SLD ice shape msmt	I	Univ. Illinois
3.5.2	Develop new measurement method	TBD	
3.6	**Humidity Measurement**		
3.6.1.1	Define capabilities of current instruments	TBD	
3.6.1.2	Compare capabilities to rqmts in Task 3.1	TBD	

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4.0 Universal Methodology

4.0 Universal Methodology	4.1 Assess Capabilities	4.2 Compare Facilities	4.3 Identify Common Methods	4.4 Document Practices

- **Icing research facilities will have different capabilities and limitations relative to simulating the SLD environment.**

- **Therefore, methods developed under tasks 1.0 thru 3.0 of this WBS should be generalized to provide guidance to other icing research facilities.**

- **The intent is provide a "template" for development of SLD simulation methods, which can be adapted to the unique requirements of each facility.**

Concluding Remarks

- An international cooperative effort has been undertaken to develop engineering tools for simulation of SLD icing conditions
- A technology roadmap was created to identify the logic path leading to development of the desired engineering tools
- A WBS was developed to identify the required research activities including performing organizations and resource requirements
- Some of the activities have been initiated or completed, others have yet to be started and some require identification of performing organizations

Concluding Remarks

Research to date has included:

- SLD simulation capabilities in the IRT
- Ice shape data from in-flight measurements
- Droplet splashing
- Mass loss due to splashing
- Scaling
- Collection efficiency
- Instrumentation